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TECHNICAL MEMORANDUM

X-96

COMBUSTION STABILITY OF A HYDROGEN JET ISSUING FROM A CYLINDRICAL SPRAY BAR

By Paul D. Reader and John W. Sheldon

Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON November 1959

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL MEMORANDUM X-96

COMBUSTION STABILITY OF A HYDROGEN JET ISSUING FROM A CYLINDRICAL SPRAY BAR*

By Paul D. Reader and John W. Sheldon

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SUMMARY

The limiting values of the geometric and local flow variables are determined for stable combustion of an unobstructed hydrogen-fuel jet issuing from a cylindrical spray bar. An extensive map of blowout conditions at pressures between 0.15 and 1 atmosphere is presented. A range of blowout velocity from 21 to 660 feet per second was covered.

INTRODUCTION

Theoretical advantages of using hydrogen fuel in a high-altitude high-flight-Mach-number ramjet engine have been shown in reference 1. These advantages are a result of the high reactivity and cooling capacity of hydrogen.

For an inlet air pressure above 1 atmosphere and an inlet air velocity below 300 feet per second, efficient ramjet combustors utilizing hydrogen fuel have been developed which do not require flameholders but seat the flame at each fuel injection orifice on a spray bar (refs. 2 and 3). This configuration becomes inefficient and unstable at more severe inlet conditions (ref. 4). Reference 5 reports combustor blowout at comparatively mild flow conditions for an unobstructed hydrogen jet issuing from a combustor wall. The recirculation zone behind a spray bar would be expected to permit flame stabilization at more severe flow conditions than would be possible with jets issuing from combustor walls.

The program reported herein was designed to determine the effects of geometric and local flow parameters on blowout pressure for a hydrogen jet issuing from a spray bar.

Various spray-bar configurations were tested in a 3- by 5-inch-cross-section combustor. Geometric variables studied included spray-bar

*Title, Unclassified.

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diameter, injection orifice diameter, injection direction, and orifice spacing. Spray-bar diameters ranged from 0.188 to 0.675 inch; orifice diameters from 0.028 to 0.081 inch. The hydrogen jets were directed normal to the airstream (injection direction, 90°) for most of the tests. The injection direction was varied with one configuration from upstream (injection direction, 0°) to downstream (injection direction, 180°). The effect of jet interaction on stability was determined by varying the distance between orifices in the range from 0.25 to 0.75 inch. These tests were conducted with fuel at approximately room temperature. Tests were then conducted with one spray-bar configuration using hydrogen at a temperature of approximately 1200° F.

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Combustor pressure at blowout was determined for airflows of 1.5 to 6.7 pounds per second per square foot of combustor cross section (21 to 660 ft/sec) and fuel flows per orifice of 0.05 to 2.4 pounds per hour. All tests were conducted with air at approximately room temperature.

APPARATUS AND PROCEDURE

Combustor Installation

A schematic diagram of the combustor installation is shown in figure 1. Air of the desired quantity and pressure was drawn from the laboratory air supply system, metered with a sharp-edged orifice, passed through the combustor, and exhausted into the altitude exhaust system. Airflow and combustor-chamber-inlet pressure were regulated by remotely controlled valves with bypass lines and valves for fine adjustments. The rectangular 3- by 6-inch duct was reduced at the test section to 3 by 5 inches by a faired 1-inch-thick block. The fairing was used in a previous program (ref. 5) to minimize the boundary layer at a wall jet injector. Figure 2 shows how the spray bars were mounted perpendicular to the duct wall.

A retractable single-electrode spark wire provided ignition for starting the combustor.

The fuel flowed from compressed gas cylinders through regulating and metering devices to the fuel injector. A critical flow orifice was used to determine the flow rate. Fuel temperature and pressure were measured immediately upstream of this orifice.

The test-section and fuel injection static pressures were measured both by manometers and by pressure transducers. Outputs from the transducers were recorded on an automatic balancing X-Y potentiometer.

Fuel Heater

Fuel temperatures of approximately 1200° F were attained with the use of an electrical resistance heater. The fuel was passed through a 3-foot length of 3/8-inch heavy-wall Inconel tube which served as the element for the heater. Up to 3000 watts of power was available from a variable low-voltage transformer.

Procedure

Data were taken in the following manner: Predetermined values of fuel and airflow rates were set, with the combustor pressure at a sufficiently high value to establish a stable flame. After combustion was stabilized and the spark electrode withdrawn, the combustion pressure was slowly reduced. The flame was observed through a window in the test section, and, when blowout occurred, a manually applied input to the X-Y recorder identified the value corresponding to combustor pressure at blowout. Blowout was recorded when all jets were out.

Test Conditions

Blowout pressure was determined for the following flow conditions:

Airflow per square foot of combustor cross section, lb/sec	1.5 to 6.7
Inlet air velocity, ft/sec	21 to 660
Fuel flow per injection orifice, lb/hr	0.05 to 2.4
Combustor pressure, atm	0.15 to 1

Inlet Air Velocity Profile

A velocity survey made in the cross-section plane of fuel injection at two typical combustor-inlet conditions indicated a relatively flat profile, varying less than ±8 percent from the average velocity. A four-tube total-pressure rake was used to measure pressures at seven vertical stations in the duct. The velocity profiles (fig. 3) were computed from these total pressures, the static pressure, and the air temperature.

RESULTS AND DISCUSSION

The combustion stability data are tabulated in table I and presented in figures 4 to 11. Blowout pressure is used as the dependent variable. A separate graph is presented for each orifice and spray-bar configuration. For a given airflow the plotted curve represents the minimum pressure of combustion, that is, blowout. Unstable combustion was frequently observed when operating at pressures within about 0.5 inch of mercury of the curve.

Effect of Flow Parameters

The airflow rate presumably affects the stability only via the associated parameters of pressure, velocity, and temperature. An increase in airflow resulted in blowout occurring at higher pressure and higher velocity. Apparently, the adverse effect of increased velocity may be overcome by a roughly proportional increase in pressure.

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At constant airflow a minimum blowout pressure occurs at a comparatively low (subsonic) fuel flow. Blowout pressure was reduced at the highest fuel-flow values; however, at this condition the fuel jet penetrated across the combustor, and blowout pressure was more likely to be dependent on the duct geometry than the orifice geometry.

Injection angles between normal and slightly downstream from normal (90° < fuel direction < 135°) were the most unstable, that is, highest pressure at blowout. This instability may be connected with the separation of the boundary layer of the spray bar which occurs in this vicinity.

The variation of stability with spray-bar diameter is shown in figures 5 and 6. Cross plots of these data at three airflow values are given in figure 7. The 0.625-inch-diameter spray bar produced less stable flames than the 0.375- or 0.188-inch-diameter spray bars. The 0.625-inch-diameter spray bar was not large enough to make blockage of the duct a factor affecting stability.

The effect of varying the distance between the fuel orifices along the axis of the spray bar is shown in figures 5 and 8. Cross plots of these data are given in figure 9 for three values of airflow. The 0.50-inch orifice spacing produced more stable operation (lower blowout pressure) than either the 0.25- or 0.75-inch orifice spacing for the temperature considered. Generally, the most unstable combustion was obtained with the 0.25-inch spacing.

Combustor blowout pressure as affected by fuel orifice size is shown in figures 5 and 10. Comparison of the data of figures 5 and 10(b) at constant values of fuel and airflow shows that the combustor blowout pressure obtained with the larger orifice (0.081-in. diam.) was somewhat lower than that obtained with the 0.052-inch orifice at fuel flow values below about 0.8 pound per hour per orifice. Above this value, the data with the 0.052-inch orifices were generally at a lower blowout pressure. Note that the 0.028-inch orifice configuration consisted of four jets, two injecting upward toward the top of the duct and two injecting downward.

The limited data taken on the 0.028-inch orifice configuration were due to fuel flow limitations.

Effect of Fuel Temperature

A 0.375-inch-diameter spray bar with two 0.052-inch-diameter normal injecting orifices spaced 1/2 inch apart was used to determine the effect of an increase in fuel temperature on blowout pressure. The data are given in figure 11. The curves on this figure are from figure 5 (fuel at 85° F). Comparison of the data points with the curves indicates that the increase in fuel temperature from 85° to 1200° F did not produce a marked effect on combustion stability for the particular configuration studied. A slight decrease in stability was consistently observed at the elevated temperature.

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Effect of Geometric Parameters

The effect of injection angle on stability is illustrated in figure 4. At low airflows, upstream injection was the most stable, probably caused by the mushrooming fuel jet acting as a flameholder. The stagnant end of the bar, which was not cooled by the flow of fuel, was heated to a bright orange. At high airflows maximum stability occurred with downstream injection. With an airflow of 6.7 pounds per second per square foot and a pressure of 4.2 inches of mercury, blowout velocity was registered at 660 feet per second.

CONCLUDING REMARKS

Upstream injection, although stable for lower airflows, reduced the momentum of the gas stream and could lead to severe heating of spray-bar and adjacent hardware. Downstream injection would lead to increased combustor length and temperature profile control problems. Normal injection, although giving good fuel distribution over the duct, was comparatively unstable. The greatest instability occurred when the orifice was in the boundary-layer separation zone of the spray bar.

The thinner, higher speed boundary layer around a large spray bar may account for the reduced flame stability with the larger spray-bar diameter.

Stability is probably effected by having a correct fuel-air ratio with the proper proximity to the spray bar. The shift in stability data with different orifice spacings may be due to the movement of the correct fuel-air ratio zone in and out of an optimum zone of stabilization around the spray bar.

High-temperature fuel tests were limited to one configuration only, and the indication that stability is not greatly affected by fuel temperature may not hold for other configurations.

SUMMARY OF RESULTS

The following results were reached concerning the combustion stability of a hydrogen fuel jet issuing from a spray bar:

1. Upstream fuel injection was the most stable at low airflows; downstream injection was the most stable at high airflows; normal injection was the most unstable at all airflows tested.

2. The 0.625-inch-diameter spray bar produced less stable flames than the 0.375- or 0.188-inch-diameter spray bars.

3. For the temperature range tested an optimum injection orifice spacing of 0.5 inch was found.

4. Raising the fuel temperature from 85° F to approximately 1200° F did not produce a marked effect on combustion stability for the configuration studied.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 28, 1959

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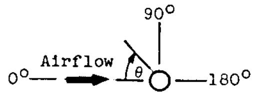
TABLE I. - COMBUSTION STABILITY DATA



(a) Number of orifices, two; fuel temperature, 85° F; air temperature, 85° F; bar size, 0.375 inch; orifice spacing, 0.5 inch; orifice size, 0.052 inch

Injection angle, deg	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec
180	1.9	0.4	10.2	78.1
180		.8	20.2	39.4
150		.8	25.7	31.4
150		.4	15.8	51.2
135		.4	23.8	34.0
135		.8	23.5	34.5
120		.8	21.5	37.7
120		.4	23.5	34.6
90		.4	21.1	38.4
90		.8	17.4	46.6
60		.4	12.6	64.3
45		.4	9.7	83.5
30		.4	7.0	115.7
0		.4	4.2	192.9
0	4.2	.4	5.1	344.6
0		.8	3.7	474.9
30		.8	10.9	161.2
30		.4	23.6	74.5
30		.4	19.6	89.7
45		.4	21.9	80.2
45		.8	14.5	121.2
60		.8	18.8	93.5
60		.4	22.4	78.5
90		.4	26.7	65.8
90		.8	26.2	67.1
90		.8	27.2	64.6
120		.8	29.1	60.4
135		.4	25.6	68.6
150		.4	14.3	122.9
180		.8	13.4	131.2
180		.4	3.5	502.1
0	6.7	.8	8.6	321.7
0		.4	18.9	146.6
30		.8	20.9	132.4
45		.8	23.9	115.8
45		.4	25.0	110.7
60		.8	29.3	94.6
135		.4	24.5	113.1
150		.8	25.2	109.6
150		.4	12.5	221.3
180		.4	4.2	658.5
180		.8	6.9	399.8

(b) Number of orifices, two; fuel temperature, 85° F; air temperature, 85° F

Bar size, in.	Orifice size, in.	Orifice spacing, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec
0.1875	0.052	0.5	2.9	0.408	20.6	58.4
				.560	17.8	67.6
				.693	17.2	70.0
				.896	15.2	79.1
				1.125	14.6	82.4
				.684	19.8	60.8
				.996	16.4	73.4
				1.438	14.6	82.4
				1.754	14.3	84.1
			3.4	.325	24.0	58.7
				.486	21.2	66.4
				.672	19.5	72.3
				.834	18.4	76.6
				1.022	15.9	88.6
				.731	22.1	63.8
				1.000	19.6	71.9
				1.396	15.2	92.7
				1.730	15.2	92.7

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TABLE I. - Continued. COMBUSTION STABILITY DATA

(b) Continued. Number of orifices, two; fuel temperature, 85° F; air temperature, 85° F

Bar size, in.	Orifice size, in.	Orifice spacing, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec
0.1875	0.052	0.5	4.3	0.345	24.6	71.2
				.508	25.4	69.0
				.717	22.8	76.8
				.508	24.6	71.2
				.857	21.3	82.2
				1.03	19.4	90.3
				.684	25.1	69.8
				.932	22.0	79.6
				1.337	17.1	102.4
				1.661	16.5	106.1
				1.990	17.7	99.0
0.625			2.9	.840	25.8	47.0
				1.680	21.4	56.7
				1.190	21.1	57.5
				1.462	20.6	58.9
				.684	23.2	52.3
				.550	26.9	45.1
				.448	29.3	41.4
				.925	21.2	57.2
			3.4	.725	30.2	47.0
				.891	28.5	49.8
				1.112	21.4	66.3
				1.325	20.9	67.9
				1.610	20.6	68.9
				1.790	21.2	66.9
				.826	27.1	52.4
				.685	27.3	52.0
				.571	28.7	49.4
				.462	30.1	47.1
			4.3	1.124	27.5	64.2
				1.310	26.2	67.4
				1.500	26.3	67.1
				1.630	23.9	73.8
				1.810	24.2	72.9
				1.942	25.0	70.6
				2.080	24.4	72.3
				2.222	23.8	74.2
				1.780	26.6	66.3
				.920	28.3	62.3
				.738	30.3	58.2
				.825	29.4	60.0
0.375		0.25	2.9	.674	25.0	47.8
				.855	23.8	50.3
				1.090	22.2	54.6
				1.260	19.9	60.1
				1.482	19.6	61.1
				1.750	17.3	69.1
			3.4	1.100	24.3	58.3
				.996	23.5	60.3
				.867	25.1	56.4
				.710	26.0	54.5
				.581	26.5	53.4
				.461	26.1	54.3
				.323	25.0	56.7
				.605	25.5	55.5
				.855	27.6	51.3
				1.155	23.3	60.8
				1.483	21.4	66.2
				1.761	18.8	75.3
				1.980	17.8	79.5
			4.3	2.130	20.8	84.6
				1.855	22.4	78.5
				1.520	23.9	73.6
				1.156	27.3	64.4
				.861	28.5	61.7
		0.75	2.9	.718	27.7	43.6
				.912	21.6	55.9
				1.191	18.2	66.4
				1.427	17.3	69.8
				1.784	17.2	70.2
				.387	29.5	40.9
				.532	25.1	48.1
				.663	22.5	53.7
				.79	20.5	59.8
				.948	19.4	62.2

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TABLE I. - Continued. COMBUSTION STABILITY DATA

(b) Concluded. Number of orifices, two; fuel temperature, 85° F; air temperature, 85° F

Bar size, in.	Orifice size, in.	Orifice spacing, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec	
0.375	0.052	0.75	3.4	0.932	25.8	54.8	
				1.245	21.0	67.1	
				1.497	20.1	70.1	
				1.721	19.1	73.8	
				1.980	18.1	77.9	
				.992	20.9	67.4	
				.804	23.6	59.7	
				.604	26.4	53.4	
				.442	29.7	47.4	
			4.3	1.140	23.5	74.6	
				.955	25.8	67.9	
				.756	27.8	63.0	
				1.041	29.1	60.5	
				1.152	27.7	63.5	
				1.420	24.4	72.1	
				1.650	25.2	69.8	
				1.920	24.1	73.0	
				2.230	23.0	76.5	
		0.50	2.9	.370	22.2	54.6	
				.527	19.4	62.5	
				.682	17.7	68.5	
				.832	17.3	70.0	
				.142	15.0	80.8	
				.200	21.6	56.1	
				.263	21.4	56.6	
				.324	22.7	53.4	
				.384	21.4	56.6	
			3.4	.949	18.7	75.7	
				1.128	16.4	86.4	
				1.427	13.6	104.1	
				1.802	13.8	102.6	
				.369	24.5	57.8	
				.525	22.2	63.8	
				.680	20.0	70.8	
				.834	18.0	78.7	
				.989	13.9	101.9	
			4.3	.888	24.7	71.3	
				1.069	21.5	81.9	
				1.280	18.6	95.0	
				1.578	16.1	109.4	
				1.878	16.1	109.4	
				.383	25.0	70.4	
				.538	25.7	68.5	
				.696	23.9	73.7	
				.850	22.4	78.6	
				1.016	24.5	71.9	
				.171	19.2	91.7	
				.230	24.4	72.2	
				.292	23.9	73.7	
				.354	25.3	69.6	
			6.7	2.039	21.5	129.4	[illegible]
				1.821	21.9	127.0	6646
				1.610	25.2	110.4	5798
				1.418	26.0	107.0	9365
				1.212	28.7	96.9	11415
				.345	28.2	98.6	11033
				.502	33.0	84.3	15087
				.578	28.9	96.3	11587
				.832	29.7	93.7	12417
				.140	17.9	155.4	4440
				.202	19.6	142.0	5356
				.263	20.4	136.3	5769
				.324	23.3	119.4	7541
				.384	25.0	111.3	5657

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TABLE I. - Concluded. COMBUSTION STABILITY DATA

(c) Number of orifices, four (0.028-in. diam.) and two (0.081-in. diam.); fuel temperature, 85° F; air temperature, 85° F

Bar size, in.	Orifice size, in.	Orifice spacing, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec
0.375	0.028	0.5	1.54	0.0480	25.0	25.5
				.0590	29.3	21.8
				.0712	29.4	21.7
				.0846	26.8	23.8
				.0976	24.7	25.8
				.131	22.9	27.8
				.144	22.4	28.5
				.1655	21.9	29.1
				.1835	21.4	29.8
				.205	20.5	31.1
				.220	20.2	31.6
				.274	19.9	32.1
	0.081		2.9	.276	12.2	82.3
				.373	14.2	70.7
				.538	15.8	63.5
				.815	15.9	63.1
				1.040	17.2	58.4
			3.4	.303	13.5	102.8
				.405	16.0	86.7
				.586	17.8	72.0
				.798	17.7	78.4
				.977	19.1	72.6
				1.120	18.6	74.7
				.660	19.0	74.6
				.754	20.9	67.8
				.920	19.5	72.7
				1.083	19.3	73.4
				1.247	18.1	78.3
				1.406	19.1	74.2
				1.568	18.0	78.7
			4.3	.360	14.0	139.9
				.504	16.8	116.5
				.716	19.6	99.9
				.724	19.7	89.5
				.913	22.3	79.0
				1.095	21.7	81.2
				1.237	22.0	80.1
				1.380	20.9	84.3
				1.518	20.3	86.8
				1.732	19.9	88.6
				1.880	19.8	89.0
				2.045	19.5	90.3
				2.205	19.5	90.3
				2.365	19.1	92.3

(d) Number of orifices, two; fuel temperature, 1200° F; air temperature, 90° F

Bar size, in.	Orifice size, in.	Orifice spacing, in.	Airflow rate, lb/(sec)(sq ft)	Fuel-flow rate, lb/hr-orifice	Combustor static pressure, in. Hg abs	Air velocity, ft/sec
0.375	0.052	0.5	2.9	0.440	22.5	53.8
				.667	22.0	55.0
				.895	18.9	64.0
				.380	23.3	51.9
				.263	25.3	47.8
				.183	25.0	48.4
				.138	19.1	63.3
			3.4	.539	25.1	56.1
				.827	24.3	57.7
				1.038	19.5	71.9
				.136	20.5	69.0
				.190	24.8	57.0
				.289	26.5	53.4
				.391	26.7	53.0
			4.3	1.104	20.8	84.8
				.820	26.0	67.8
				.576	27.8	63.4
				.167	21.5	81.9

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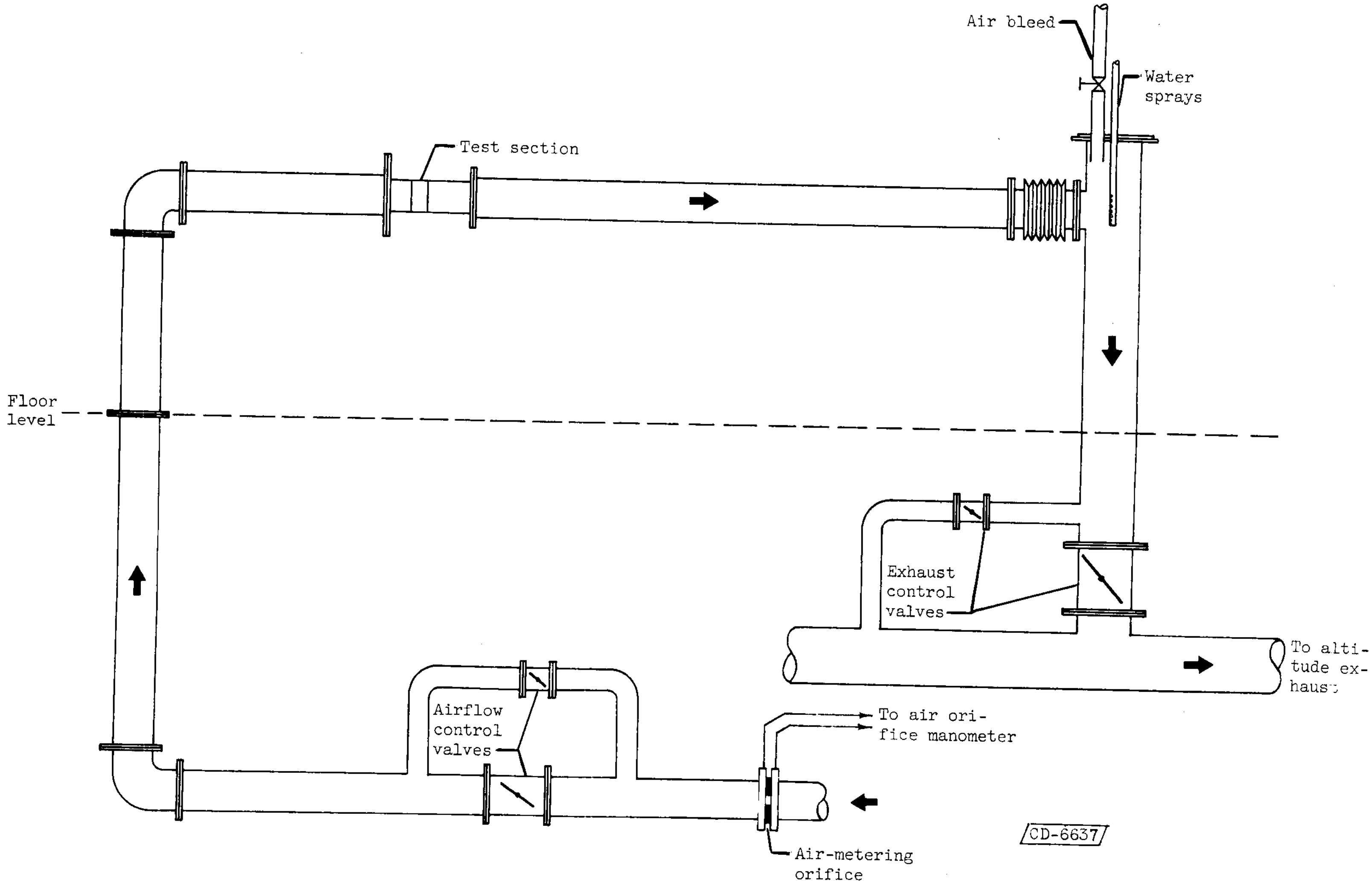

Figure 1. - Test facility.

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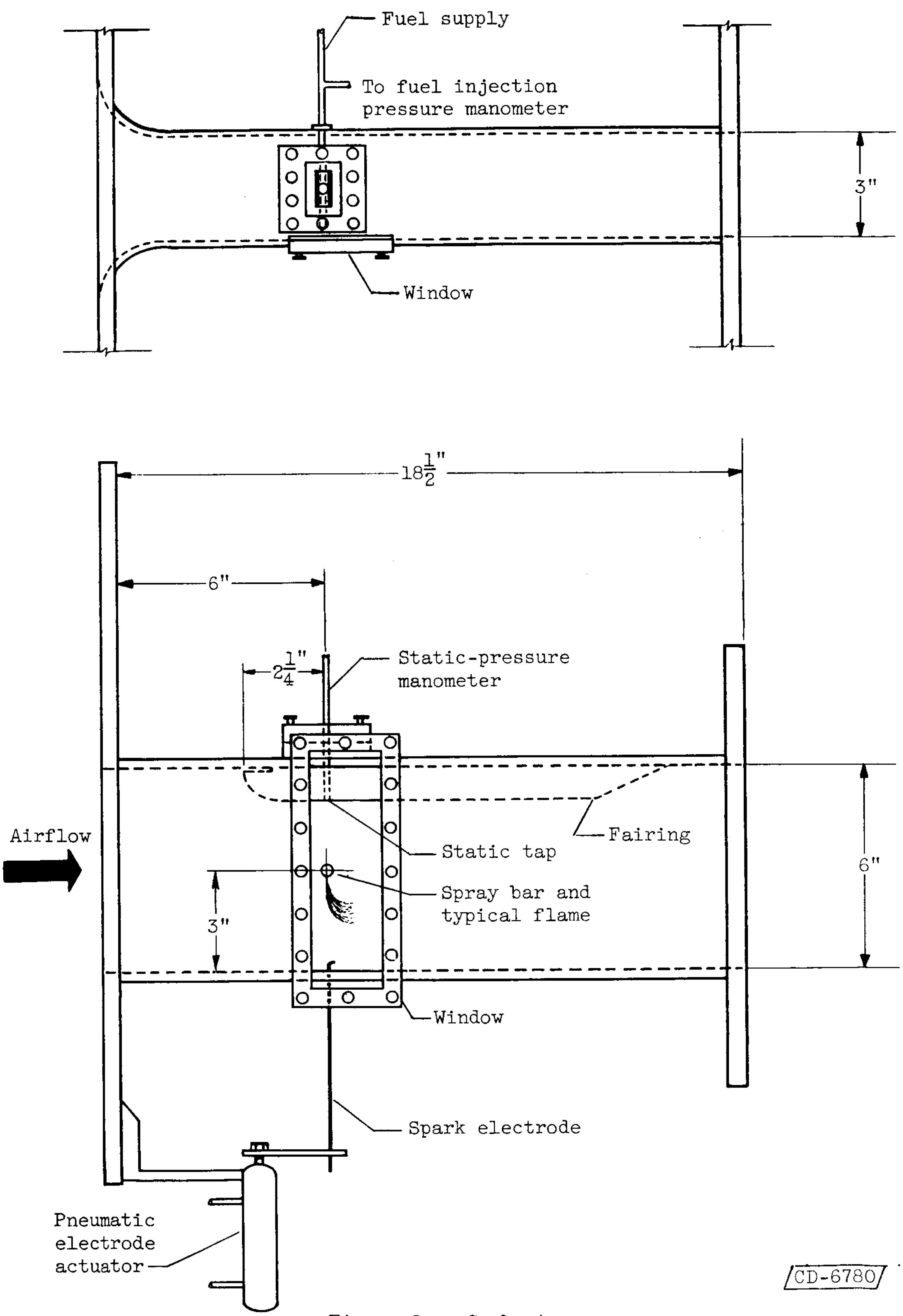

Figure 2. - Combustor.

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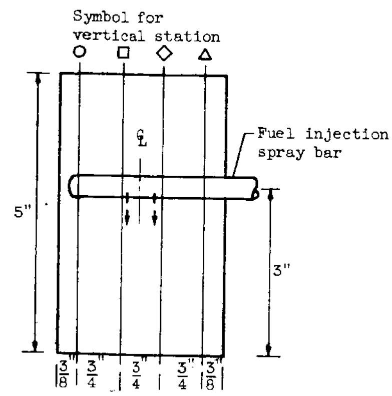
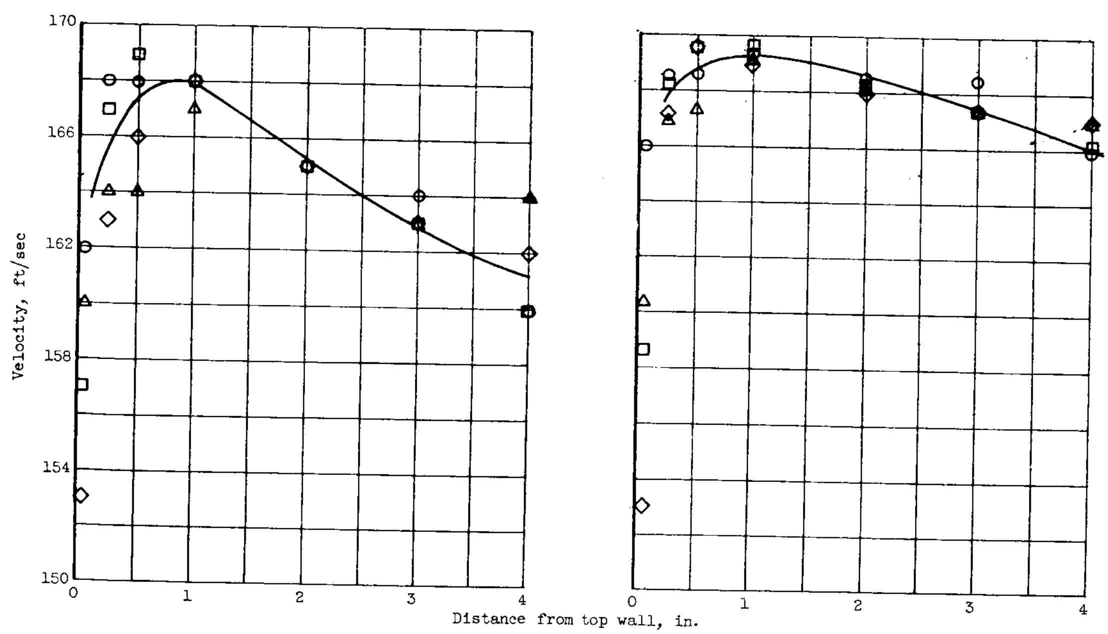
E-401



Combustor cross section at point of fuel injection, looking downstream



(a) Combustor static pressure, 26.8 inches of mercury absolute.

(b) Combustor static pressure, 14.0 inches of mercury absolute.

Figure 3. - Combustor-inlet air velocity profile.

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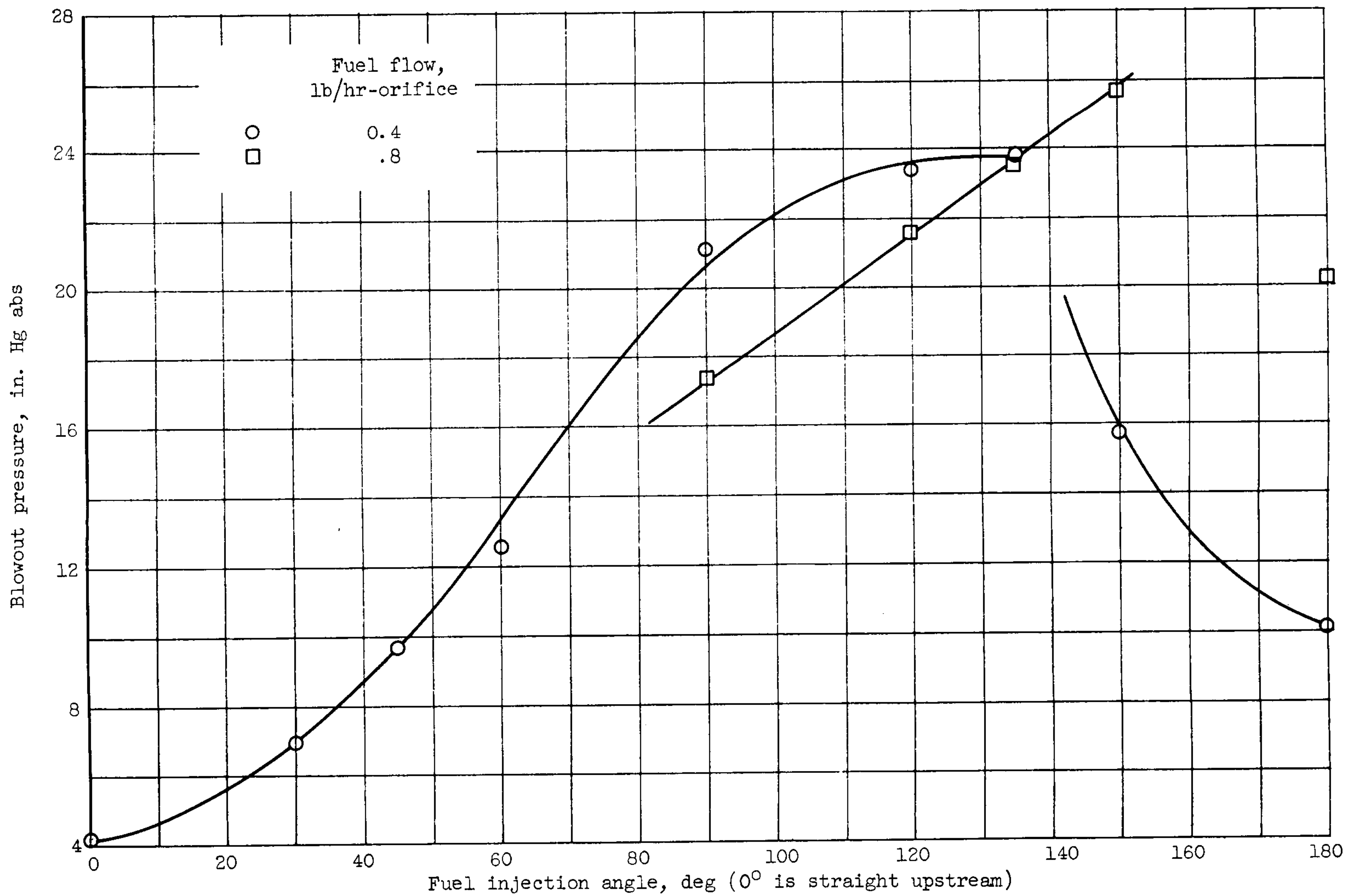

(a) Airflow, 1.9 pounds per second per square foot.

Figure 4. - Variation of combustion stability with fuel injection angle.

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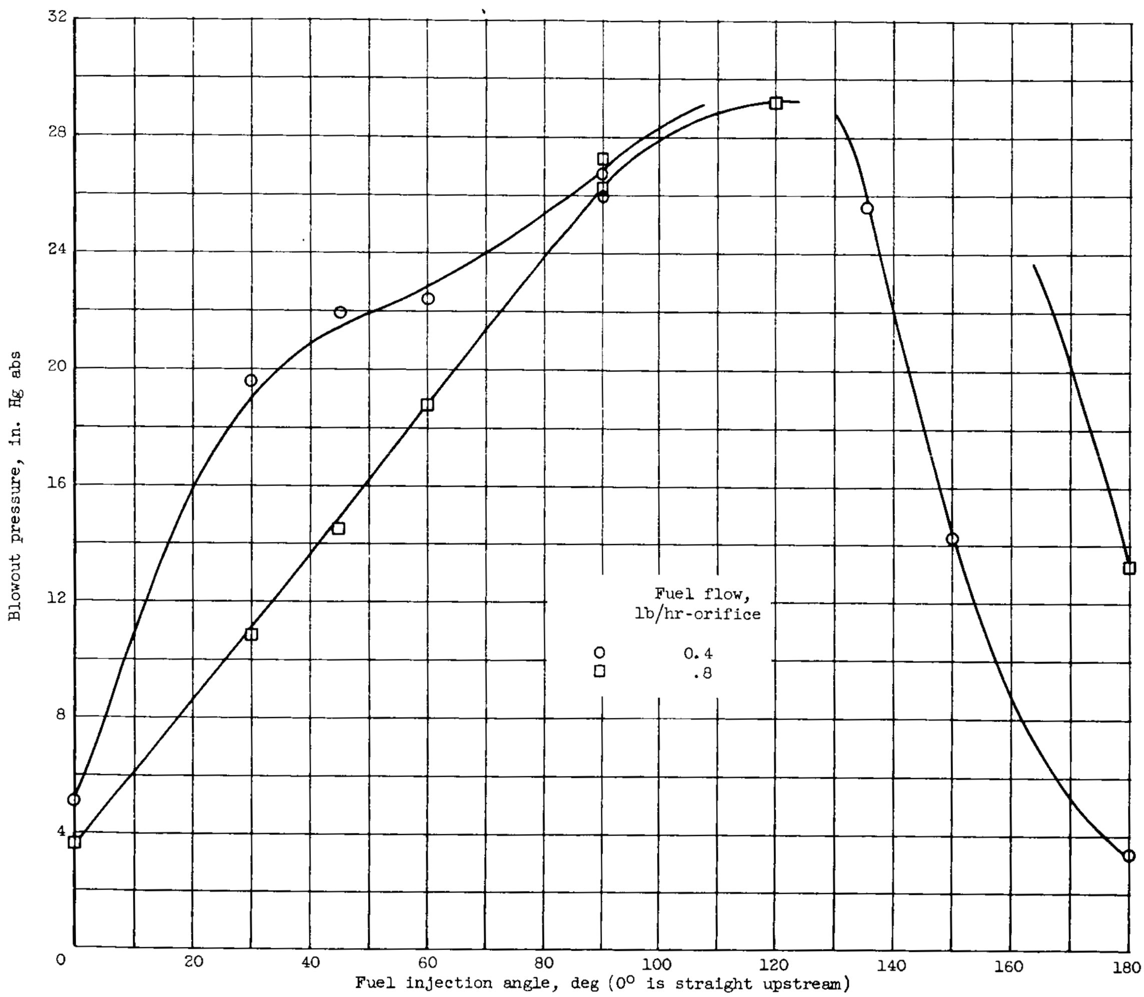
E-401



(b) Airflow, 4.2 pounds per second per square foot.

Figure 4. - Continued. Variation of combustion stability with fuel injection angle.

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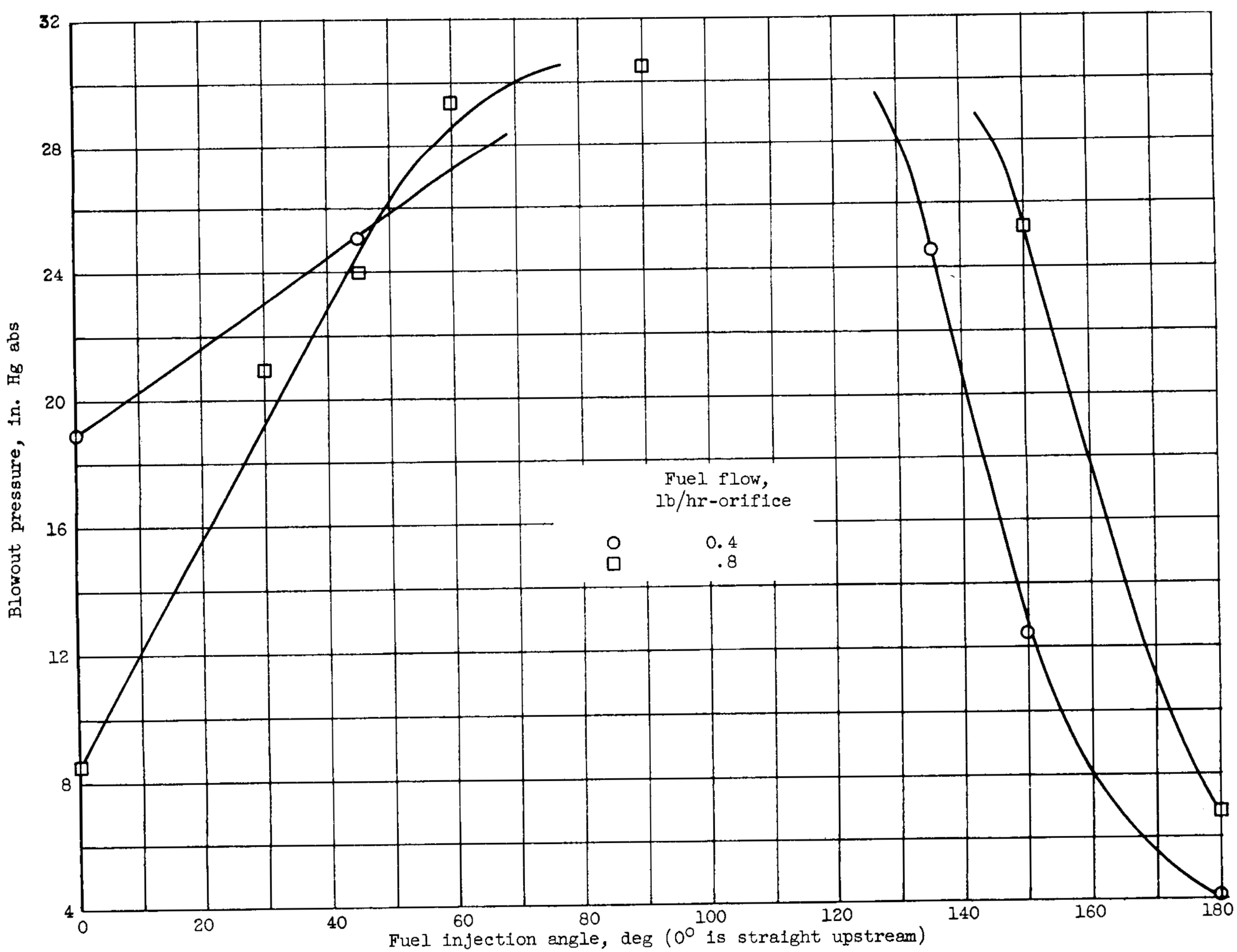

(c) Airflow, 6.7 pounds per second per square foot.

Figure 4. - Concluded. Variation of combustion stability with fuel injection angle.

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E-401

CM-3

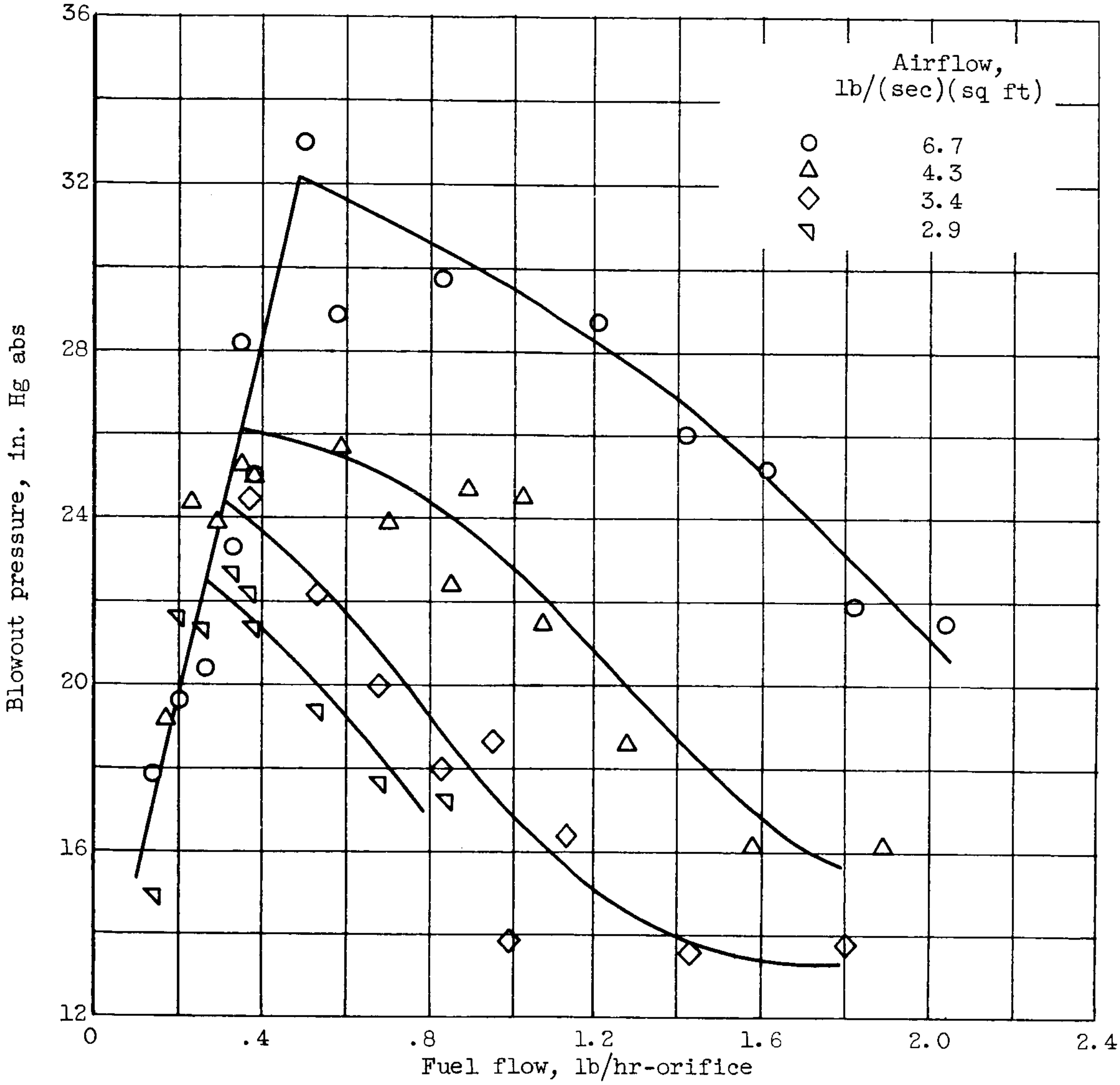

Figure 5. - Variation of blowout pressure with fuel flow. (Two 0.052-in. orifices spaced 0.5 in. apart on a 0.375-in.-diam. spray bar.)

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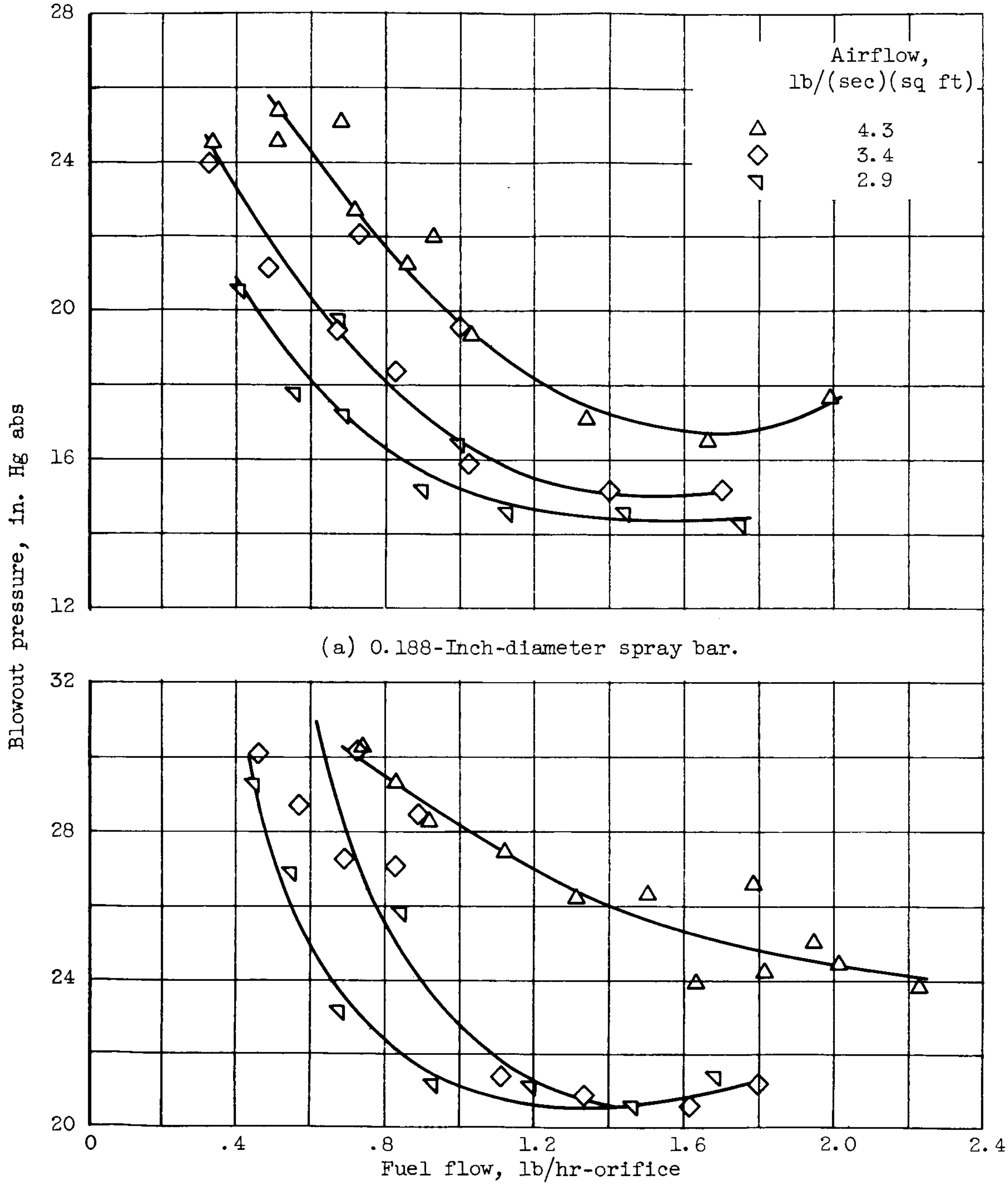
E-401



(a) 0.188-Inch-diameter spray bar.

(b) 0.625-Inch-diameter spray bar.

Figure 6. - Effect of spray-bar size on blowout pressure for two 0.052-inch orifices spaced 0.5 inch apart.

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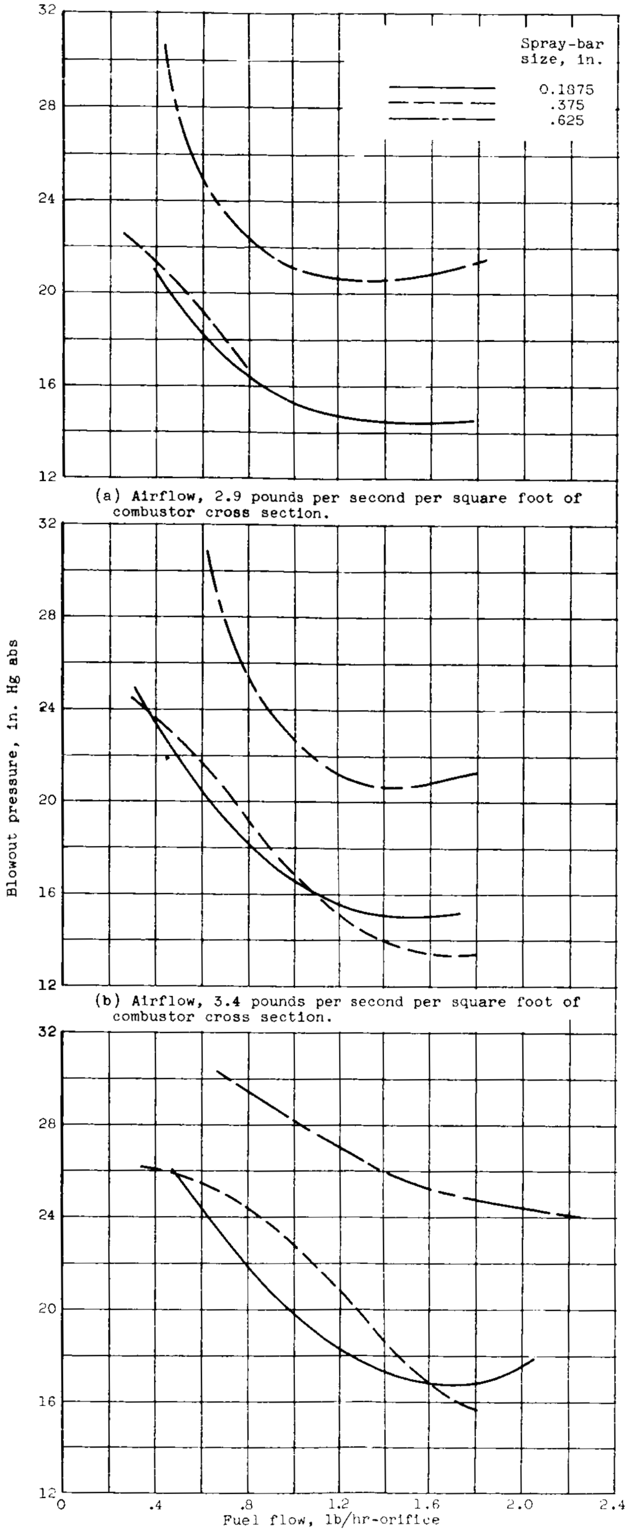
E-401

CM-3 back



(a) Airflow, 2.9 pounds per second per square foot of combustor cross section.

(b) Airflow, 3.4 pounds per second per square foot of combustor cross section.

(c) Airflow, 4.3 pounds per second per square foot of combustor cross section.

Figure 7. - Variation of stability with spray-bar size with constant orifice separation.

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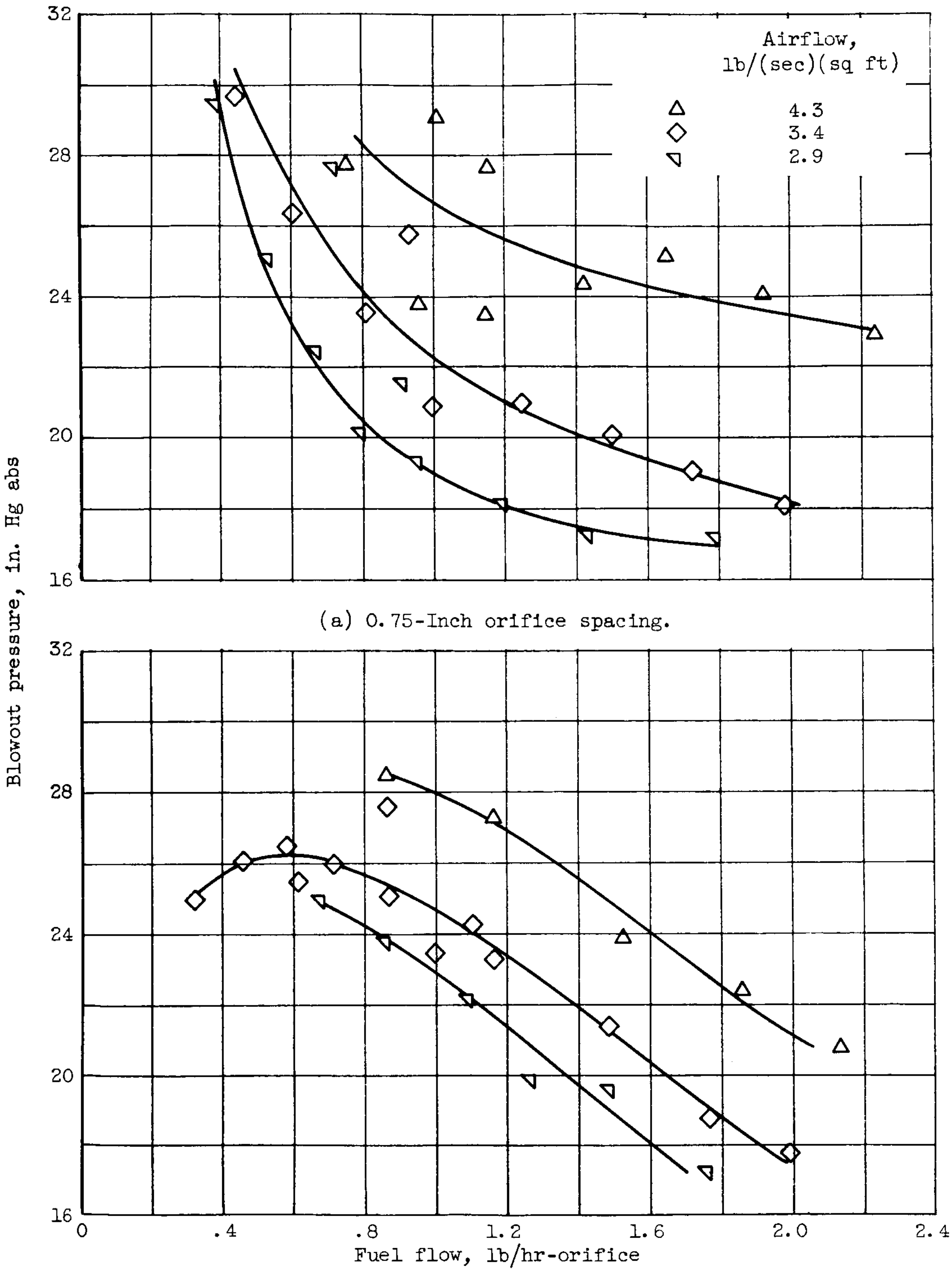
E-401



(a) 0.75-Inch orifice spacing.

(b) 0.25-Inch orifice spacing.

Figure 8. - Effect of orifice spacing on blowout pressure for two 0.052-inch orifices on a 0.375-inch-diameter spray bar.

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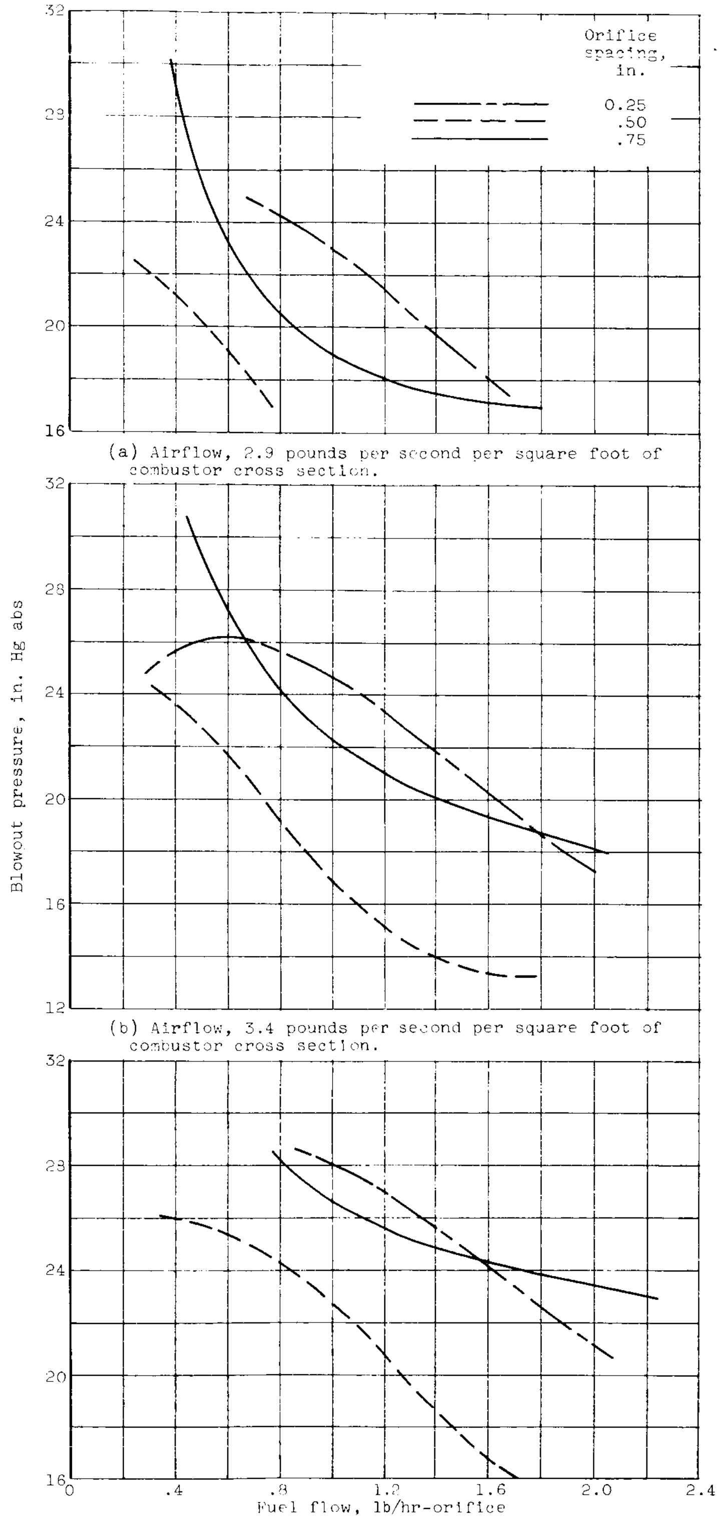
E-401



(a) Airflow, 2.9 pounds per second per square foot of combustor cross section.

(b) Airflow, 3.4 pounds per second per square foot of combustor cross section.

(c) Airflow, 4.3 pounds per second per square foot of combustor cross section.

Figure 9. - Variation of stability with orifice spacing with constant spray-bar size.

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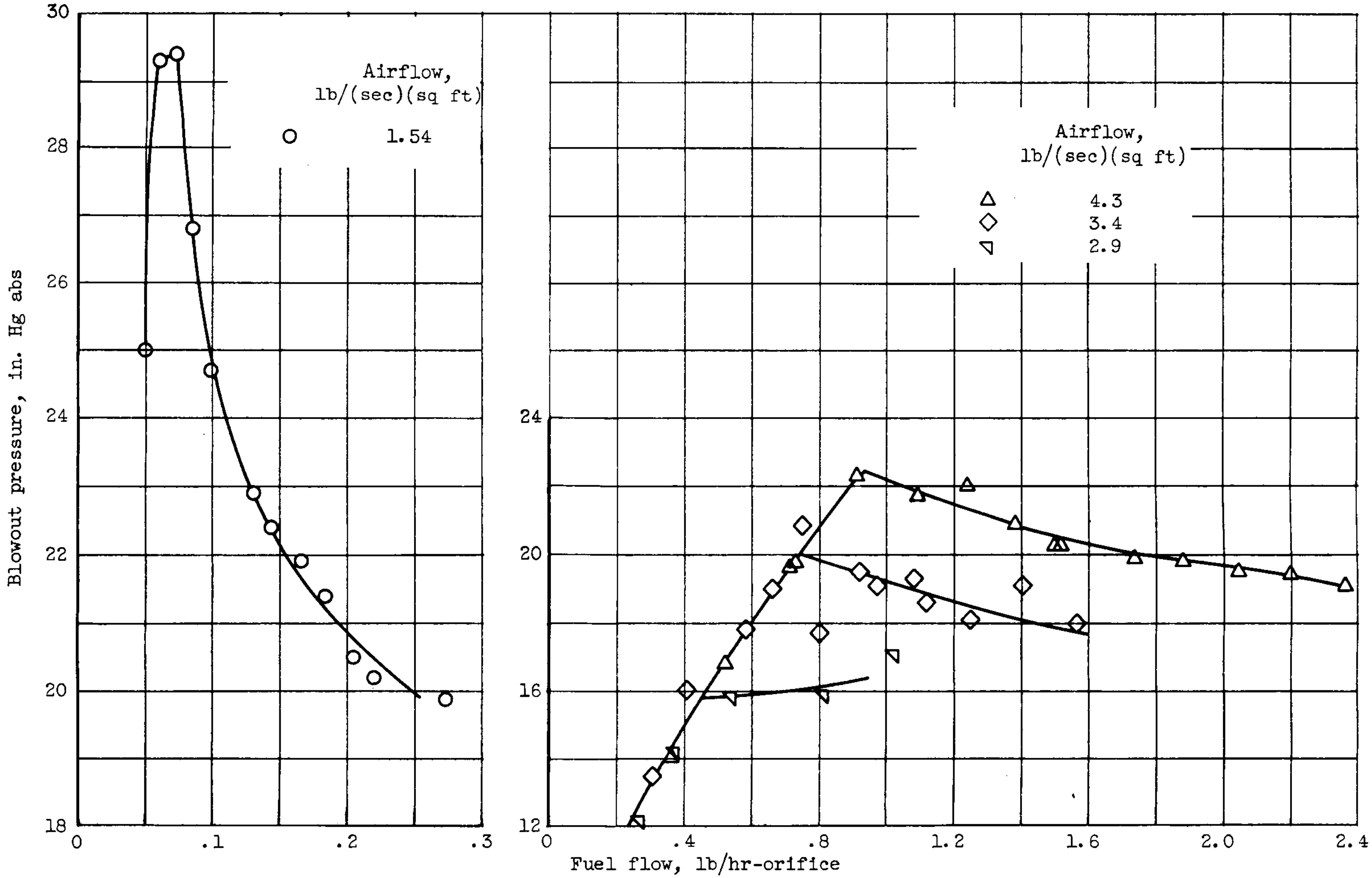

(a) 0.028-Inch orifices spaced 0.5 inch apart on a 0.375-inch-diameter spray bar.

(b) Two 0.081-inch orifices spaced 0.5 inch apart on a 0.375-inch-diameter spray bar.

Figure 10. - Variation of blowout pressure with fuel flow.

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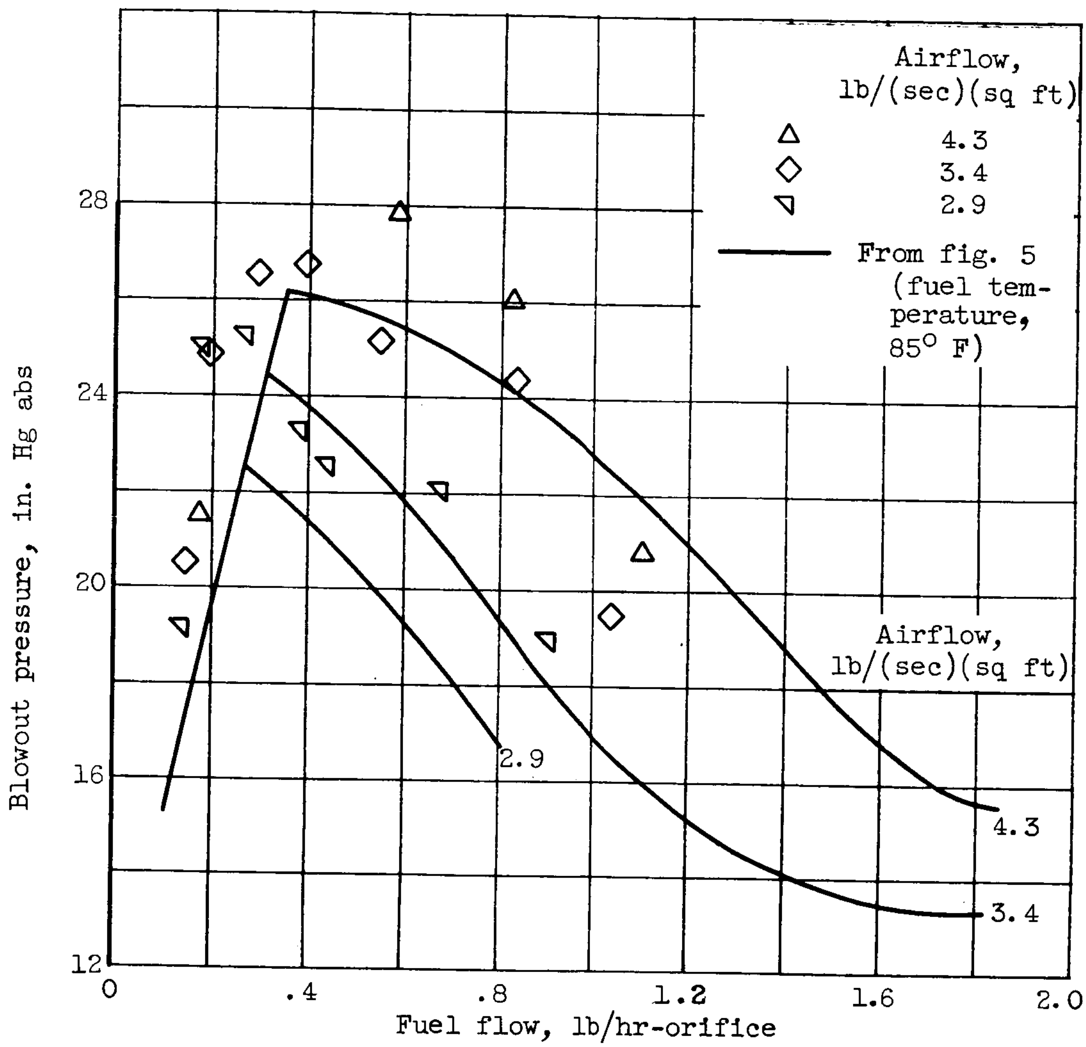

Figure 11. - Effect of fuel temperature on blowout pressure for two 0.052-inch-diameter orifices spaced 0.5 inch apart on a 0.375-inch-diameter spray bar. Fuel temperature, 1200° F.